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State of the art of biofuels from pure plant oil

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ABSTRACT

The pollution caused by fuel combustion either for mechanical or electrical energy generation purposes is nowadays one of the most important environmental issues. It has been proven that combustion emissions, particularly those from cars and trucks, are linked with severe damages to the environment and human health. Along with the environmental problems, is necessary to consider that fossil resources are declining and their exploitation is getting more and more expensive. Bioenergy represent a sustainable solution for energy generation. Bioenergy is renewable energy made from plant-derived organic matter, collectively termed "biomass". Biomass-based energy sources are potentially carbon dioxide neutral and recycle the same carbon atoms. Life cycle assessments are reported to evaluate the net environmental impacts of biofuels. The term biofuel refers to liquid or gaseous fuels for the internal combustion engines that are predominantly produced from biomass. Biofuel policy might capitalize on the production of biofuels supporting rural economic development and sustainable agriculture. Amongst biofuels pure plant oil (PPO) has been investigated. This paper sets out to review the state of the art for PPO use as fuel in diesel engines, based on a wide literature review.

Contents

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1. Introduction

Fuels from crude oil supply about 96% of the worldwide energy demand for transportation [1]. On the other hand, known petroleum reserves are limited and will eventually run out. Various studies put the date of the global peak in oil production between 1996 and 2035 [2–9]. Declining supplies of fossil energy resources such as oil, coal, natural gas, as well as the high cost of dependency on their importation are core problems that European Union countries must face; this is the rationale of several strategies to promote the use of biofuels (see REFUEL project in [10]). Fossil fuels fatal flaw is that its reserves may be 80% depleted within 35–84 years, depending on how rapidly it is used. Based on current projections, with the actual rate of consumption, global oil reserves are expected to last at least 44 years [11], without considering possible undiscovered mineral deposits that might prolong fossil's supply for other 20–40 years [12,13].

Renewable energy systems seem a promise to solve all these problems, granting many countries energy supply security and being environmentally friendly. There are many reasons for the interest in biofuels; amongst all we cite:

- mitigate climate change and reduce dependency on energy imports;
- the production of renewable energy to substitute the conventional fossil fuels, even though effectiveness of this replacement is still questionable [14];
- the virtually global commitment to reduce greenhouse gas emissions (GGE);
- the development of local resources: support to companies and small-scale producers, well-being and added value;
- significant cost savings in transportation [15].

The concept of renewability quantification is interesting to apply to better address these aspects, evaluating in particular the restoration work with respect to the produced work (see, e.g., renewability indicator in [16]).

Depletion of global fossil oil joint to climate change and global warming issue have driven European Union energy policy towards three main goals: (a) assure security energy supply reducing dependency on oil imports, which will lead to (b) strengthen the countries economy guaranteeing, at the same time, the environmental protection [1,17,18].

Among all sectors, the one that more is dependent on fossil fuels is the transportation sector.

Diesel engines are broadly used in the transport, electricity generation, construction equipment and stand-by power generators [19,20]. These sectors are heavy consumers of petroleum oils that are susceptible to be partially or totally replaced by biomass fuels, and their derivatives, derivable from agriculture and thus of renewable origin [20–26]. One interesting note on this concern is from [27], who highlights the need to evaluate the thermodynamical efficiency of making a fuel transportable (in the liquid form), since this factor might help to understand the most promising feedstocks to endeavour for the transportation, with particular concern to the pure plants.

The use of pure plant oil or PPO is yet marginal, but it seems to be very interesting for its future potential [28].

1.1. Biofuels and their use in diesel engines

The term biofuel refers to those liquid or gaseous fuels, used for the transport sector, that are predominantly produced from biomass [29,30]. Only biodiesel and bioethanol are presently produced as a fuel on an industrial scale: a short history in their use and production is provided in [31] or [32]. Biodiesel is one of the candidate alternative energy sources that fulfills sustainable criteria because it is renewable and produced from domestic resources with less environmental impact, but also because it is biodegradable and non-toxic [33].

Increased use of biofuels offers many benefits, as well as sustainability, reduction of greenhouse gas emissions, and decreased reliance on foreign oil [17,34]. Besides being a renewable source, in fact, such oils are CO_2 neutral and contain little, if any sulphur, nitrogen and metals, which are major pollutants in current fuel emissions [35].

A variety of fuels can be derived from biomass resources including liquid fuels,[1] such as hydrogen and methane [36]. The use of biofuels is wide since they are mainly used in vehicles but are suitable in engines or fuel cells for electricity generation. Several strategies has been experimented for their application to the transportation sector since 80s (see for instance the results reported in [37]).

Due to their low sulphur levels, biofuels have insignificant sulphur dioxide SO_2 emissions compared to diesel oil. Furthermore many of them present also low nitrogen levels [17,30,38,39]. Nevertheless the biggest difference between biofuels and fossil fuels is oxygen content: biofuels present oxygen levels of 10 up to 45% while petroleum has essentially none [23,40]. The high oxygen content, if on one hand causes poor thermal stability and lower volatility [40], on the other hand contributes to a complete fuel oxidation, thus to a complete evaporation of the liquid fuel [41].

Essentially, liquid biofuels may be made from a variety of biomass sources through a number of conversion routes. Feedstock for their production are mainly the so called “first-generation” and “second generation” conversion pathways depending on the scope of crops, namely food use or biofuel dedicated one, and then the third generation [18] crops which are designed exclusively for fuels production and are commonly referred to as “energy crops”(such as perennial grasses, fast growing trees, and algae): this matter is of extreme importance for biofuel policy deployment [42,43]. The core of sustainability question is the balance between subtraction of direct or indirect human feeding resources (e.g. subtracting arable land [44], the biofuel controversy in [45]) versus CO_2 emission reduction for transportation. Mainly, biofuels fall into the following categories:

(a) vegetable oils and biodiesels,
(b) alcohols,
(c) bio crude and synthetic oils.

Production of biofuels corresponds only to 1% of fuel requirements at the present day; it is expected to reach 7% in 2030 passing from a first generation of today to the carbon negative biofuels of 2030 [46]. The question of sustainability of biofuels is of great interest indeed to the present reasoning too, thus stressing on the importance of LCA concern for comparing biofuels [28,33,44,47–50]. Also blending strategies of pure oils with liquid hydrocarbon fuels seems to be an effective strategy to pursue [51].

Fig. 1 shows the sources of main liquid biofuels for diesel engines.

The use of plant oils in compression ignition (CI) engines is not new: Rudolf Diesel, the inventor of the engine that bears his name, during the Paris Exposition of 1900 exhibited his very first engines fuelled with peanut oil. These early uses were sporadic and petroleum derived fuels soon emerged as the dominant transportation fuel, although in the few decades, the increased costs of gasoline and the depletion of fossil feed stocks has led to a

[1] For liquid fuels are meant all those combustible with similar chemical and physical properties to fossil fuels, that can be used in diesel engines.

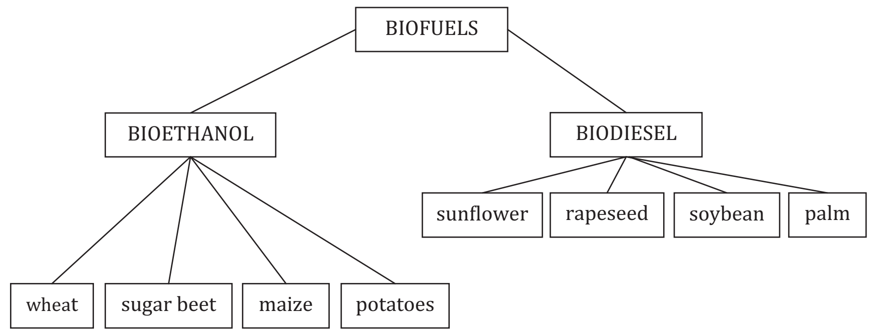


Fig. 1. Sources of main liquid biofuels for automobiles [30].

significant growing in the consumption of fuels derived from plant oil. Currently about 0.7% of worldwide diesel fuels derive from vegetable oil [52,53], using several different processes for upgrading their properties for combustion purposes (pyrolisis [54,55]; an overall review is provided in [35], catalytic cracking [56–58]).

1.2. Features of common vegetable oils

Plant derived oils can be obtained from a wide variety of oilseed plants such as sunflower, rapeseed, soybean, castor and from the seeds of plants grown for textile fibres, mainly cotton and flax. Furthermore oil-bearing fruits mostly from coconut palms (coconuts containing copra), walnut trees, oil palms (palm fruits and kernels), *Jatropha curcas* L. or purging nut (Euphorbiaceae) and olive trees (olive) are other source of biofuel [59]. Today, waste vegetable oils can also be used for the production of PPO or biodiesel, traditionally used as an animal feed component. They have the advantage of being a readily available waste product, though thorough cleaning is necessary to remove contaminants that would quickly block fuel filters or damage the engine fuel system [28].

Different species of vegetable oils have been used in CI engines during the years, although only a fraction of them have been used and investigated thoroughly. For an extensive and significant review of these can refer to [60].

In Table 1 several kinds of plant oils are reported that have been tried in diesel engines at some time or other. Biodiesel has been mainly produced from edible vegetable oils all over the world. More than 95% of global biodiesel production is made from edible vegetable oils, however the rapidly growing world population and rising consumption of bio-fuels are increasing demand for both food and bio-fuels. Hence the production of biodiesel from different non-edible oilseed crops has been extensively investigated over the last few years [61]. An mess of different biospecies are being experimented so far as feedstock for biofules (see [62–65]).

Table 2 shows the properties of 18 oils for which substantial data are available [66,67].

As Table 2 shows, plant derived oils are a viable alternative to petroleum oil because of the similarity in their physical and chemical properties. Therefore, when biofuels are fed into diesel engines, they behave like analogous fuels in the combustion chamber, but on other hand they have the advantage of being biodegradable, non-toxic and, carbon dioxide neutral as they are of plant origin [68]. Blends of such oils should be also considered, indeed, from thermal efficiency point of view; this seems to be not so different from traditional petroleum derivated fuels [69,70]. Also an ongoing efflorescence of research are in process to find ever new and cheaper feedstocks for producing biofuels (see e.g. [71]). Still this is an open field of research, since several problems for combustion may persist: see, for instance [72].

The quality of the oil is very important in order to guarantee the correct operation of the vehicles, in particular the injectors, piston rings and lubrication oil stability. As for today, the only available standard is the German standard DIN 51 605 [28].

Biofuel oils deviations from the properties of fossil diesel are shown graphically in Fig. 2.

Vegetable oils have a higher density than diesel on an average of 12%, but lower energy content with a calorific value around 10% inferior.

Cetane number is a measure of the ignition quality of a diesel fuel, i.e. the fuel's readiness to ignite. Fuels with a high Cetane number will have short ignition delays which correspond to greater efficiency; contrarily engines started with a low Cetane number fuel may suffer from engine knock and blow white clouds of smoke during engine ignition in severely cold weather. The Cetane number for most plant oils, it is around 10–20% lower than that of fossil diesel [59,61,66,67].

Kinematic viscosity and *density* are important characteristics to consider because they affect the fuel spray characteristics through flow resistance inside the injection system and in the nozzle holes [34]. High viscosity causes poor fuel atomisation during the spraying process, which in turn increases the engine coke deposits, demands more energy in order to pump the fuel and wears fuel pump elements and injectors [73]. For plant oils viscosity is higher and volatility lower than for fossil diesel.

Flash point temperature is the lowest temperature at which the vapour of a combustible liquid can be ignited in air. The flash point of vegetable oils is much higher than that of diesel. This makes its ignition relatively difficult, but its transportation and handling is much safer [74]. The *Pour Point* of a liquid is the lowest temperature at which it will pour or flow under prescribed conditions. Plant oils show an higher flash point temperature and lower pour point temperature in respect to fossil diesel.

The *carbon residue* value correlates with the carbonaceous deposits inside the combustion chamber and injector systems. Its formation is due to the way the fuel is injected and ignited in the diesel engine: when the fuel is injected, in the compression cycle, it is ignited spontaneously due to compression pressure and the air and fuel do not have a chance to mix thoroughly before ignition. The presence of fuel dense pockets, in the mixture, results in incomplete combustion of the fuel and the production of carbon soot or BC particulate matter [17]. In such incomplete combustion instances, the carbonaceous deposit for plant oils it is considerably higher than for fossil diesel [9].

1.3. Effects on engine performance

Several types of plant oils have been tried and compared in CI engines. Extensive literature is available on examining the performance variation obtained among using different types of plant

Table 1
Examples of potential edible and non-edible plant oils for use in CI engines [66].

Edible oil	Non-edible oil
Sunflower oil, rapeseed oil, rice bran oil, soybean oil, coconut oil, corn oil, palm oil, olive oil, Pistachio Palestine oil, sesame seed oil, peanut oil, opium poppy oil, safflower oil	Jatropha oil, Karanji or Pongamia oil, neem oil, Jojoba oil, cottonseed oil, linseed oil, Mahua oil, Deccan hemp oil, Kusum oil, orange oil, rubber seed oil

Table 2
Comparative properties of fossil diesel, edible and non-edible plant oils and biodiesels [66].

CI engine fuel	Properties						
Common name	Calorific value [kJ/kg]	Density [kg/m^3]	Flash point [°C]	Pour point [°C]	Kinematic viscosity at 27 °C [cSt]	Carbon residues [%, w/w]	Cetane number
Diesel	43.35	815	45–60	−6.70	4.30	0.03–0.1	47.00
Sunflower oil	39.52	918	73	−15.00	58.50	0.23	37.10
Cottonseed oil	39.64	912	234	−15.00	50.10	0.42	48.10
Soybean oil	39.62	914	254	−12.20	65.40	0.27	38.00
Peanut oil	39.80	903	271	−6.70	39.60	0.24	41.80
Corn oil	37.82	915	277	−40.00	46.30	0.24	37.60
Opium poppy oil	38.92	921	–	–	56.10	–	–
Rapeseed oil	37.62	914	246	−31.7	39.20	0.30	37.60
Sesame seed oil	39.30	913	260	−9.40	35.50	0.25	40.20
Palm oil	36.51	918	267	−31.7	39.60[b]	–	42.00
Coconut oil	35.80	915	–	–	31.59	–	–
Mahua oil	38.86	900	238	15.00	37.18[b]	0.42	–
Rice bran oil	39.50	916	–	–	44.52[b]	–	–
Jatropha oil	39.77	918	240	–	49.90	0.20/0.44	45.00
Pongamia oil	34.00	912	263	–	37.12	–	–
Jojoba oil	42.76	863	292	6.00	25.48[b]	–	–
Rubber seed oil	37.50	922	198	–	39.91[b]	–	37

[a] At 38 °C.
[b] At 40 °C.
[c] At 37.8 °C.

oils and in some cases even with the same type of oil [66,75,76]. It is known that fuels with high viscosity cause several serious problems for engine performance and operation. To test the engine performance, variables like engine load, producer, speed, feedstock homogeneity, ambient conditions, injection type (direct or indirect), are the ones that mainly affect the results. Plant oil temperature is another key factor in the engine performance assessment. Nwafor [128] tested the shift in the performance of a diesel engine fed with vegetable oil inlet a different temperature, stating an improvement in the engine performance for temperatures higher than 55 °C. This is due to the viscosity–temperature relationship.

The *brake power output* of engines running on pure plant oils or blends varies in the range of +10% to −18% compared to engines running on fossil diesel under similar operating conditions. However, according to most reports there is a power decrease of around 2–18% caused by (i) higher viscosity, which interferes with the injection process and leads to poor atomisation, leading in turn to incomplete combustion, some un-burnt plant oil and loss of power; and (ii) the low calorific value of plant oil [9].

The *brake specific fuel consumption*[2] for plant oils and all blends is about 4–8% more than for fossil diesel. The higher specific fuel consumption may be due to lower calorific value and higher density of vegetable oils [20].

The *brake thermal efficiency*[3] of pure plant oils and all blends change according to the engine load and speed [77–79]. This variation is almost the same for diesel fuel though. In particular the b.t.e. of vegetable oils is in the range of 3% more to 10% less than fossil diesel. The reasons for this may be the higher viscosity of the blends and lower volatility of vegetable oils. In a study [22] has been found that the slow burning of vegetable oils can be compensates starting the combustion earlier. Therefore, to obtain an higher brake thermal efficiency, it is sufficient to advance the injection timing.

1.4. Effects on exhaust emissions

Results of several researches [41,66,77,79–85] state that for CI engines operated on biofuels, emissions of CO and NO_x were found to be higher, whereas unburned HC emissions were lower compared to fossil diesel.

The engine load strongly influences the emissions rate of vegetable oils. CO and HC emissions decrease as the load increases, although, on the other hand, this led to higher NO_x emissions [81,82].

The correlation CO emissions-load engine is due to a better fuel/air equivalence ratio in case of heavy loads. In this case blending the vegetable oil with diesel could bring to a better performance, diminishing oil viscosity and poor spray atomisation, key factors in exhaust emissions [23].

NO_x is produced during the combustion process, when nitrogen and oxygen are present at elevated temperatures. Due to higher combustion temperature in the engine cylinder, also NO_x emissions increase as the engine load increases. Therefore the combustion temperature represent the main variable to regulate NO_x emissions. It is important to highlight that most vegetable oils contain small quantities of nitrogen proteins, responsible of higher NO_x emissions during the combustion respect to diesel fuel [24].

NO_x is extremely dangerous since is 292 times more effective than CO in increasing greenhouse effect. Also in this case, blending the vegetable oils with other fuels represents a solution to decrease the NO_x rate [20].

A better result was found for the unburned HC emissions, which are lower than diesel fuel. However this reduction is the largest at no-load and gets smaller as the load increases; the minimum rate of un-burnt HC emissions is reach at full engine load [24].

[2] Is the mass rate of fuel consumption per unit brake power.
[3] Is defined as the ratio between the brake power output and the energy of oil/fuel combustion.

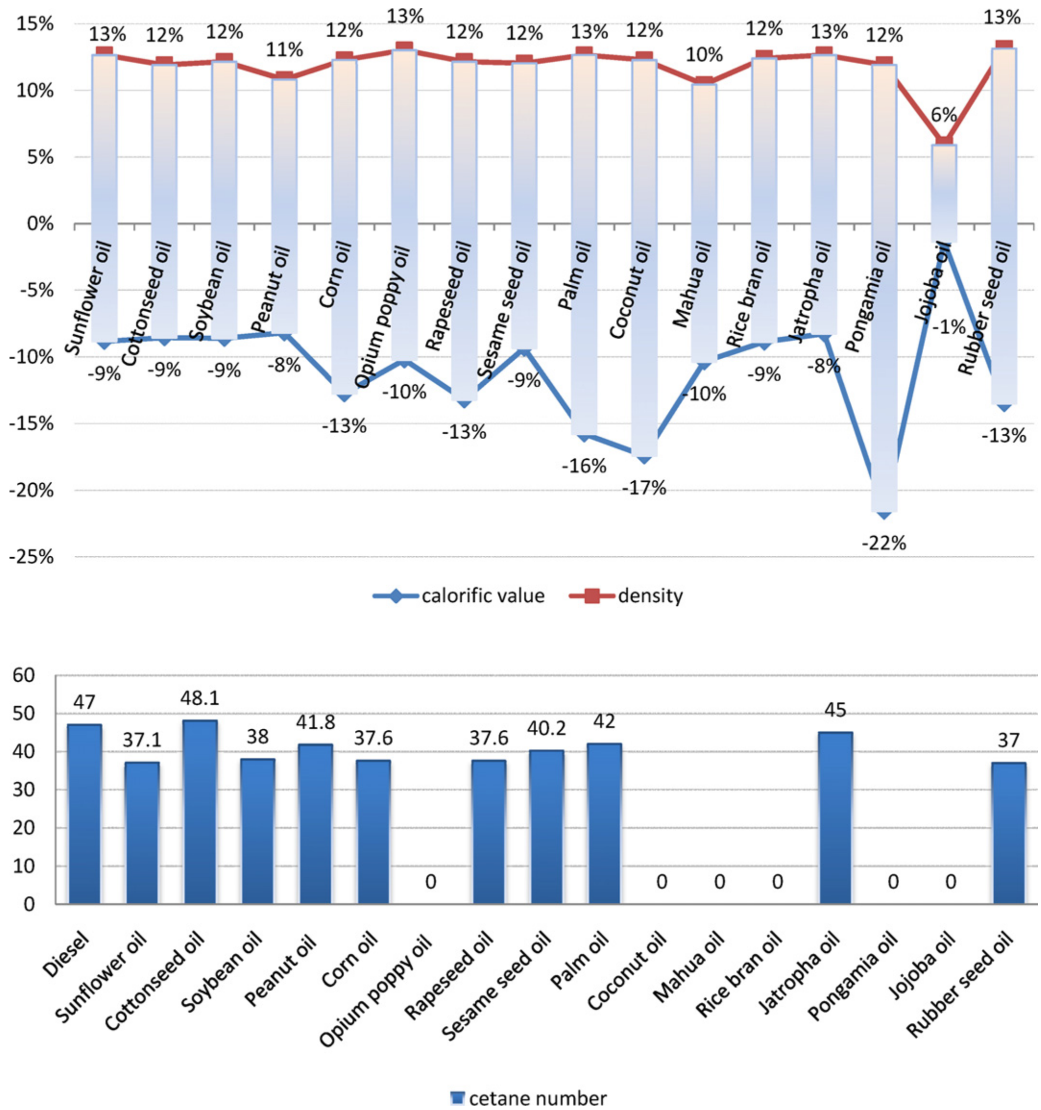


Fig. 2. Differences between plant oils properties and fossil diesel properties.

It has to be noted that results vary significantly according to the engine specifications, type, operating condition and vegetable oil used.

Possible solutions to decrease exhaust emissions are discussed further in the paper.

In Fig. 3 are summarised the different exhaust emissions rates for different vegetable oils.

CI engines running both on pure or blend sunflower oil have the best exhaust emissions performance. The most important gas to take into account is NO_x. Since it is more influent than CO in the global warming, its reduction does curry more relevance.

Rapeseed oil, the most cultivate crops in Europe, presents emissions rates almost equal to fossil diesel, when runs in CI engines.

Conclusively it can be stated that the particulate emissions reduction is more significant at low load. Vegetable oils present good performance as fuel, even though some engine problems were found in literature due to their higher viscosity and low volatility. Such problems are: carbon deposits on injector tip, piston rings and cylinder walls. Those problems bring up to another inconvenient: the dilution and thickening of the lubricating oil. Therefore using vegetable oil for long hours may led to choke the fuel filter causing break or failure of some mechanical members in the engine [53,59,81,86].

Overall the problems associated with plant oils usage in CI engines can be divided into durability problems and operational problems. The first ones include carbonization of injector tip and all the deposit formation. The second ones involve combustion and engine performance [25].

To face those difficulties various solutions have been proposed that concern engine modification or fuel modification. The engine modifications involve:

- Preheat vegetable oils before to starting up the engine,
- Adapt the injection system to vegetable oils viscosity,
- Dual fuelling the engine starting up with diesel oil and then switching to pure plant oil,
- Exhaust gas recirculation (EGR) in the engine.[4]

The fuel modifications involve:

- Blend vegetable oil with biodiesel, ethanol or/and pure diesel,
- Transesterification, pyrolysis and emulsification of plant oil.

[4] Exhaust gas recirculation (EGR) is another approach to improving the exhaust gas emissions of plant oil fuelled engines. A small amount of exhaust gas is fed back into the cylinder, lowering peak temperatures and reducing the formation of NO_x.

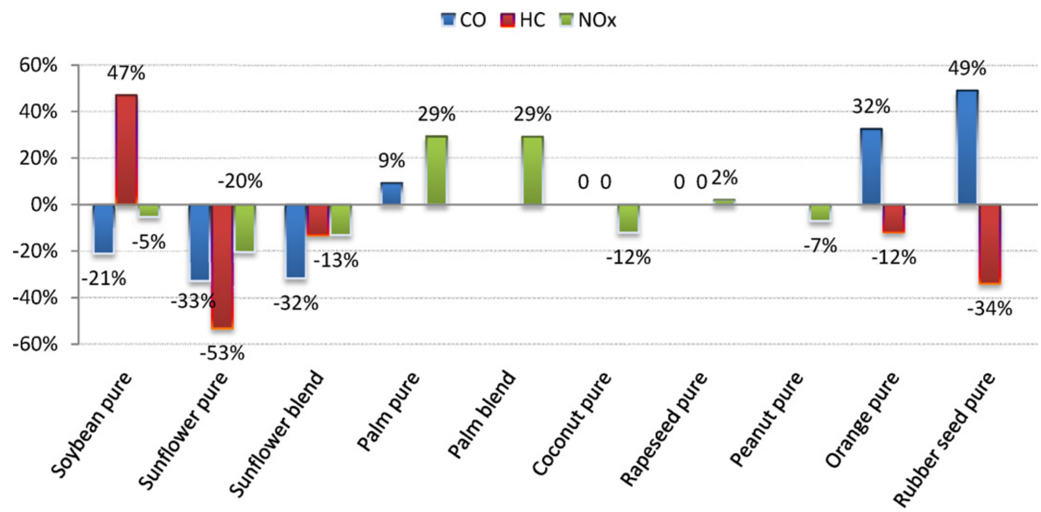


Fig. 3. CO, HC and NO_x emission of CI engines running on plant oil (or blend with fossil diesel) as compared to fossil diesel [9].

There are several studies [52,53,66,77,84,87,88] in which the fuel heating is investigated. It has been proved that preheating the vegetable oil assure a viscosity 80% lower than unheated oil, and similar to diesel fuel. Also carbon monoxide and dioxide production is almost the same for both heated and unheated oil at low loading conditions. Although at high engine load there is an higher CO_2 emission of the heated fuel respect to the unheated and diesel fuel.

Therefore preheating vegetable oil is emission beneficial only at low speed and part-load operations.

Transesterification, pyrolysis and emulsification are process use during the biodiesel production, thus are not taking into account in this review, which is focused on pure plant oil usage.

Further, two valid systems to use straight vegetable oil as fuel are reported.

2. Pure plant oil usage in diesel engines

Diesel engines are designed to burn diesel fuel, which has a lower viscosity than vegetable oil. Therefore the direct usage of pure plant oil in the engine leads to poor fuel atomisation and incomplete combustion, which can rapidly damage the engine. Pure vegetable oil thickness is the central problem for their use since it is 11–17 times thicker than conventional fuel. If the fuel is too thick it will not atomise properly when the fuel injectors spray it into the combustion chamber and it will not combust properly. Furthermore the injectors get coked up, leading to poor performance, higher exhaust emissions and reduced engine life [59,80,83,88,89].

In CI engines the use of vegetable oils can be successfully achieved through fuel and engines modifications. A simple fuel modification can be obtained by blending the PPO with diesel or biodiesel; Modification of the injection system, fuel preheating and dual fuelling belong to engine adaptation. Heating [90–92] and blending [87,93] of vegetable oils reduce the viscosity but its molecular structure remains unchanged in a polyunsaturated form and low volatility problems exist [30].

2.1. Generality

Pure plant oil (PPO), also referred as PVO (Pure Vegetable Oil) or SVO (Straight Vegetable Oil), is the use of plant and vegetable oils without any modification to their chemical structure as a fuel to be combusted inside a diesel engine. This method should not be confused with bio-diesel, which is a fuel derived from pure plant oils through a transesterification process that splits fatty acids from glycerine to reduce the viscosity of the pure plant oil similar to that of mineral diesel.

In Europe mostly rapeseed oil is used as PPO. In the German system of water pollution classes [38], rapeseed oil is classified in the lowest class 0, whereas bio-diesel is in class 1, and fossil diesel is in class 2.

Unlike biodiesel, the use of PPO requires to modify the engine. The best way is to fit a professional kit to the diesel engine which includes replacement injectors and glow plugs optimised for vegetable oil, as well as fuel heating.

The engine modifications necessary to run a diesel engine with vegetable oils can be divided into two categories: one tank systems and two tank systems.

Both focus on plant oil viscosity and low volatility in order to avoid carbonaceous deposits, poor atomisation and incomplete combustion, with consequently damage engines and low engine performance. The viscosity is the main characteristic that has to be control, as PPO is about ten times more viscous than mineral diesel and trying to spray it through an injector designed for a fluid so much less viscous is similar to trying to spray butter through a washing up liquid bottle.

2.2. Two-tank PPO systems

With two-tank PPO kits one tank holds the vegetable oil and the other petro-diesel (or biodiesel).

The engine is started on the petro-diesel tank and runs on petro-diesel for the first few minutes while the vegetable oil is heated to lower the viscosity. Fuel heaters are electrical or use the engine coolant as a heat source. When the fuel reaches the required temperature, usually 70–80 °C (160–180 °F), the engine is switched over to the second tank and runs on PPO.

Illustrated in Fig. 4, is a two tank system for pure plant oil. Items “O” and “N” represent the two tanks, which are installed inside a vehicle. Vegetable oil in its un-transesterified form can also be used in diesel engines but it has to be heated, because modern engines are fitted with injection systems designed to deliver and properly atomise diesel fuel, which has a viscosity of approx. 8 centistokes. The example heating systems and peripherals in Fig. 4 include “M” which is a heater located inside in the vegetable oil tank and “E” which is normally a special type of heat exchanger, that transfers heat to the engine cooling oil to the vegetable oil or in cruder systems glow plugs, using power from the battery to heat the oil.

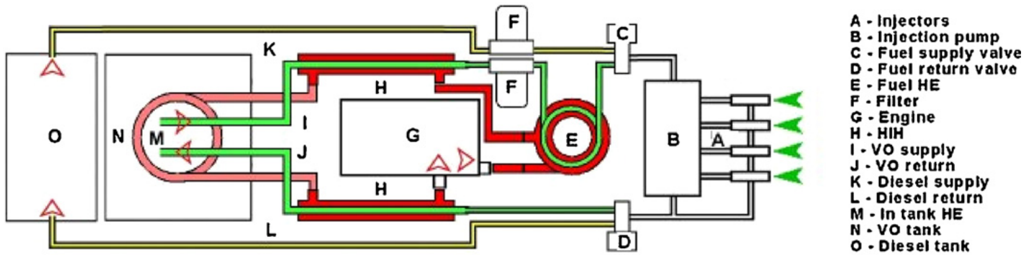


Fig. 4. Illustration of a two tank system which allows a vehicle to run on PPO [39].

Before the engine is shut down, it must be switched back to petro-diesel and the fuel system "purged" of vegetable oil before switching off, so that there is no cold vegetable oil left to coke up the injectors next time the engine is starting.

The operation of this system is that upon shut down of the engine the mineral diesel or bio-diesel from the smaller tank "O" is feed into the engine until all the vegetable oil is purged out. Upon start-up the engine is run on the mineral or bio-diesel until it reaches operational temperature and the rapeseed oil is once again feed to the engine.

Other important features of the system in Fig. 4 include, "F" which is a special type of filters especially PPO fuels such as rapeseed oil and "B" which is an injector pump which has a slightly more robust design than normal engine pumps. In some cases the injectors "A" are also replaced but there is very little literature or detail on how exactly these injectors are modified and exactly the benefits of them.

One of the few scientific studies available found that vegetable oil must be heated to 150 °C (302 °F) to achieve the same viscosity and fuel performance as petro-diesel: "Atomisation tests showed that at 150 °C the performance of the rapeseed oil is comparable with that of the diesel oil" [40].

That is double the temperature the two-tank PPO systems use. At only 70–80 °C vegetable oil is still much more viscous than petro-diesel (six times more viscous in the case of rapeseed oil, the oil specified in the German SVO fuel quality standard).

Whatever their technical merits and shortcomings, two-tank kits are better for longer-distance driving than for short stop-and-start trips [41].

2.3. One-tank PPO systems

With professional single-tank PPO systems there is no waiting or switching fuels as with two-tank SVO kits, just start up and go, stop and switch off, like any other car.

The engine starts easily and burns cleanly from the start, even at sub-zero temperatures (supplementary heating is available for really cold conditions).

The "secret" is specially made injector nozzles, increased injection pressure and stronger glow-plugs, in addition to fuel pre-heating.

Among the one-tank systems was taking into account the Elsbett conversion systems, who have more than 30 years at the forefront of using vegetable oil fuel in diesel engines.

With this system, there is no additional tank; all the fuel is held in the original tank of the vehicle. This solution relies on the adaptation of the injection process to the injection characteristics of vegetable oil, so typically, the glow-plugs, injectors, and injector mounts are modified.

The ELSBETT one-tank system can be fitted on pre-chamber diesels of most makes, as well as on TDI engines (1,4l, 1,9l and 2,5l) from the Volkswagen group (AUDI, SEAT, Skoda, Volkswagen and some Ford and VOLVO as well as 1.9 dTi motors from Renault) [52].

The typical one-tank conversion kit would contain the following parts:

- injector components
- additional fuel filter
- sometimes additional fuel pump
- coolant-water heat exchanger to pre-warm fuel
- electrical fuel heater/filter
- temperature switch
- fuel and water pipes.

The cost of both systems, single and dual, are equals and around € 1000 [94,95].

In the Scientific Laboratory of Biofuels at Latvia University of Agriculture were carried out some tests to verify the efficiency, in terms of consumption and emissions, of a diesel engine running just on rapeseed oil [53]. A VW Golf 1.9TD was opportunely modified using the ELSBETT one-tank system. The authors specify that the choice of one tank was made for facilities reasons, since the two tank would have required more space, and bureaucratic reasons, since the second fuel tank is classified as a modification, which requires a special certification.

The car was then tested along three different routes, in urban and suburban areas, comparing the engine performance before and after the conversion. The results show a slightly higher fuel consumption of rapeseed oil over fossil diesel, but significant savings against biodiesel fuel consumption. Moreover the authors pointed out that even after the car modification, it was still able to run on fossil diesel, with the only wariness of switching off the electric heating filter and the heat exchanger.

Surfing the home pages of Elsbett conversion kit manufacturer it is possible to find various examples of heavy and light duty vehicles fed with vegetable oil. In all the cases it has been highlighted that a great attention should be paid to the quality of oil used. A poor seed quality, processing and pressing can led to engine damage and bad performance. The lack of quality standard requirements or worldwide regulation for seed oils is still an issue that has to be solved [59,88,96–98].

In Europe, only Germany set out a Quality Standard DIN 51605 for rapeseed oil (RK-Qualitätsstandard) [59].

2.4. Performance of direct PPO use

2.4.1. Torque and power

Many studies have been carried out to investigate the performance of vegetable oils in diesel engines, and mostly they present different results [22,86,87,99–104]. A few of them display an approximate 10% drop in power when pure plan oil is used in CI engines instead of diesel oil [59,93]. This lower performance has been addressed to the minor net calorific value of vegetable oils compared to diesel oil.

In a study on the performance of rapeseed oil blends by Nwafor and Rice [87] it is clearly found that the brake specific fuel consumption results were comparable with mineral diesel data.

The improvement in brake thermal efficiency when compared with that for mineral diesel fuel operation was higher than expected, indicating that the chemical energy of the vegetable oil was more effectively converted to mechanical work.

When operating on PPO, a diesel engine has more or less the same (thermal) efficiency as when operating on diesel. The volumetric energy content of pure vegetable oil is only 4% lower than for diesel. So overall the volumetric fuel consumption when operating on PPO can be a few % higher than for diesel.

2.4.2. Hydrocarbon emissions

Operations with pure rapeseed oil offered a net reduction in hydrocarbon emissions compared with mineral diesel results. The 50% mineral diesel 50% rapeseed oil blend competed favourably with the neat diesel fuel and they recommend rapeseed offers a reasonable substitute for diesel fuel.

Nwafor and Rice [87] in their study, proved that the rapeseed oil and blends with mineral diesel on average reduce the hydrocarbon emissions from the engine by at least 50% and even up to 75% at mid loads.

2.4.3. Greenhouse gas emissions

PPO emits a slightly higher amount of CO_2 then regular fossil diesel per unit of energy. As the energy consumption with PPO is also about the same, the actual CO_2 emitted from the vehicle is comparable. Though, the renewable aspect of vegetable oils feedstock make them more environmental friendly. The amount of emitted CO_2 is, indeed, again adsorbed by the oil crops from which PPO is made. Theoretically, there could be a completely closed cycle, using exclusively renewable energy. However in practise fossil energy is still necessary during the agricultural process, the pressing process and in the distribution. Beyond that, the intensive use of fertilisers in agriculture is culpable for adding extra N_2O emission in the atmosphere, which is a critical active gas for the global warming.

In general, it can be settled that the overall GHG savings coming from the use of biofuels over fossil fuels are on average estimated between 50 and 80%, calculated without greenhouse gases related to land use change [66].

The literature is filled with lots of benefits for the fertility of the land and benefits for following crops and for CO_2 absorption and neutrality of rapeseed oil. A study from Denmark [67] has calculated for a rapeseed oil crop that there is a reduction from the atmosphere of 14,937 tonnes per hectare suppression as against 1604 for emissions. This would mean that CO_2 reduction from the crop is 9.31 times greater than the gross CO_2 emission.

2.4.4. Specific fuel consumption

In engine test the fuel consumption is measured as a mass flow rate per unit time second. The specific fuel consumption is the fuel flow rate per unit of power output and is a significant engine parameter. It measures how efficiently an engine is using the fuel supplied to produce work. Literature reviews show how specific consumption generally decreases with the increase in engine load. This is true for all fuels but is not valid with PPO, which displays an inferior reduction in consumption at low engine load than diesel oil in diesel engines given the higher volume consumption [68,86,101–103]. Regarding this point there is some contradiction in the literature, since some authors attested an overconsumption of approximately 8% while others found out much lower (>5%) results [20,103,105]. Overall, this higher specific fuel consumption value is addressed to the low Net Calorific Value of vegetable oils, together with their high density and high [7].

2.4.5. Carbon monoxide emission

Carbon monoxide concentrations in the exhaust is a measure of the combustion efficiency of the system. In some studies, CO emissions for vegetable oils are reported to be close to those of diesel fuel, when the vegetable oils are heated [104,106]. Other reviews settled the amount of CO emissions according to the engine load, displaying a decreasing trend with a lower engine load. The minimum value in the CO emission is reached at around 75% of the maximum engine load. At that load, the difference is 31.6% [68]. The reason for this different performance is due to the poor combustion of vegetable oils according to the lower volatility and higher viscosity. Heterogeneity of the fuel richness in the cylinders and partial oxidation of hydrocarbons in the exhaust manifold are other two factors responsible for CO emission from diesel engine [34]. Other authors have found CO emissions for vegetable oils that were comparable to, if not less than, those of diesel oil, provided the vegetable oils were heated or the injection advance was adjusted. All the results attested the importance of the air/fuel mixture and good atomisation of the fuel in the carbon emission [52,53,101,107].

3. Pure plant oil vs. biodiesel: SWOT analysis

The well known advantages of biodiesel over PPO is that it works in diesel engines without needed any conversion or adaptation of the engine, which makes it more portable and "ready to use" in current diesel engines. What is not so highlighted is that pure vegetable oil is more environmentally friendly with regard to the energy balance as has been addressed by a Danish study [66].

Originally, a SWOT analysis is a strategic planning tool used to evaluate the Strengths, Weaknesses, Opportunities, and Threats involved in a business venture. In this case, the SWOT analysis is applied to compare two similar but different types of biofuels: pure plant oil and biodiesel. They are both suitable for being used in compression ignition engines, and they both come from seed oils, nevertheless they have different production processes and then different properties.

The strength–weakness–opportunities–threat analysis of both vegetable oil was carried out based on literature reviews [67,108–113]. The SWOT analysis outcomes are shown in the following tables.

Fuel	Pure plant oil	Biodiesel
Strengths	It is successfully used as fuel in diesel engines.	The properties of biodiesel (viscosity, ignition properties) and fossil diesel are similar.
	Its production process is simple and suitable for decentralized production in small oil mills, providing increasing employment in rural areas.	It is an alternative fuel able to run on conventional unmodified engines.
	Its flashpoint make them easy to handle and store.	It has high combustion efficiency and high Cetane numbers which correspond to short ignition delays and greater efficiency.
	It has a lower energy consumption for production over biodiesel.	It has an higher lubricating effect that is significant to avoid wear in the engine.
	It is not toxic and does not generate waste products.	It presents an higher yield in oil extraction.
	It has been classified as harmless to groundwater according to the German system of water hazard classes (WGK).	Compared to fossil diesel it has a lower toxicity.

Fuel	Pure plant oil	Biodiesel
	Modified engines may run on pure plant oils, biodiesel, and fossil diesel, as well as on mixtures.	The co-product glycerine of the transesterification process can be sold.
	A fuel standard for pure oil exists in Germany DIN V 51605.	In Europe a European standard EN14214 does exist for biodiesel quality requirements.
	The side products and agricultural residues can be used as fodder, fertiliser or 2nd generation biofuels.	
	For cultivating oil crops can be employed the already existing cultivation techniques.	
	Pure oil and biodiesel have very low sulphur content, causing no emissions of sulphur dioxides.	

Fuel	Pure plant oil	Biodiesel
Weaknesses	It has very high viscosity and low volatility which can led to poor atomisation and lower engine performance.	It has an higher energy consumption for production, that is twice the amount need for pure plant oil and fossil diesel.
	It has a lower calorific value respect to biodiesel and fossil diesel, which means lower energy content, thus lower brake thermal efficiency and higher specific fuel consumption.	It needs a refinery process that is not suitable for decentralized production, thus it cannot be performed in agricultural economy, bringing to a less employment in rural areas.
	It needs a market development.	It has an higher costs for establishment and operation of production plants.
	Economic viability depends on seed yields and income from by-products (press cake).	Economic viability strongly depends on seed yields and income from by products (glycerine and press cakes).
	In Europe no common standard for pure oil exists.	It is aggressive with fuel pipes, sealings and filters, that have to be adapted.
		Non modified engines may run on biodiesel, and fossil diesel, as well as on mixtures, but not on pure plant oils.
	Long term storage of pure plant oil and biodiesel may cause degradations in certain fuel properties, requiring additives.	

Fuel	Pure plant oil	Biodiesel
Opportunities	It has a cheaper production process being only produced by pressing and filtering the oil seeds.	Currently it is the dominant biofuel in the Europe.
	It does not generate co-products such as glycerol and allows close cycle use of raw materials and products in the same territory.	It is a portability, ready available fuel that can directly feed CI engines.
	Energy policy that provides tax reductions/exemptions and biofuel obligations could largely increase use of pure plant oil and biodiesel.	
	Their use and development can realized energy supply security leading to strengthen EU economy.	
	Waste oil can be used as cheap feedstock for pure oil and biodiesel.	
	Other oil plants than rape seed can be cultivated in Europe (e.g. sun flower, soy[a]).	

[a] Also vehicles are being produced that run solely on these fuels.

Fuel	Pure plant oil	Biodiesel
Threats	It is necessary to adapt the engine to the oil fuel, thus well-built vehicle modifications have to be made.	It is toxic and polluting in case of spillage and percolation since contains solvents and other chemical additives.
		An increasing market for biodiesel will saturate the demand for glycerine and the price for this co-product will decrease.
	In Europe mainly rape seed is used as feedstock source. Rape seed can be cultivated only every four years on the same field.	
	No standard for PPO or biodiesel feedstocks exists, which means the variation in feedstock properties could vary for many different reasons.	

As the tables above show the usage of vegetable oil in a compression ignition engine cannot be undervalued [23,114,115]. PPO an biodiesel have both the potential to reduce GHGs emissions and dependency on fossil diesel.

If biodiesel needs a refinery process to modify the vegetable oil properties, PPO needs engine modifications.

In Europe pure plant oils and biodiesel, are currently mainly produced from rape seed, although other feedstock types are suitable for using.

4. Life cycle analysis

The Life Cycle Assessment methodology is an useful tool used to address the environmental impacts coming from biofuels use.

The scientific literature is full of LCA studies on biofuels, which show differing results according to the different inputs used or the different boundaries taken for the analysis [38,105,116–126].

Two of the major strengths of biofuels are their carbon neutral characteristic and renewable aspect, while generating new income for farmer and providing security energy supply. In spite of this, the GHG savings coming from biofuel use, do not appear to be so considerable.

Results from several life cycle studies evidence some environmental impacts such as eutrophication, biodiversity an ecotoxicity brought out from the intense crop cultivation. Land transformation and availability is a crucial aspect that has to be taken into account in the full biofuel life cycle.

The use of plant oils as fuel for compression ignition engines and the life cycle analysis has been reviewed by Hossain and Davies [66]. The two main indicators investigated by the authors during the life cycle assessment were: energy output-to-input ratio and GHG emissions. During their study the above mentioned authors compared pure plant oil against fossil diesel and biodiesel, breaking down the biofuel life cycle into five phases: feedstock production, feedstock transportation, fuel production, fuel transportation/distribution and end use [8]. Part of their analysis is further reported and discussed.

Environmental impacts arise all along the biofuel value chain: during the land transformation and cultivation, while using fertilisers and agrochemicals products, in the biofuel process production and then during its transportation and final use in cars [73].

In Fig. 5 is represented a simple biofuel production chain.

The major amount of pollutants is represented by CO_2, which is generated in almost every unit process of the biofuel production chain.

A simple life cycle assessment is made up of a Life Cycle Inventory (LCI), necessary to quantify all relevant flows of materials and energy along the life cycle chain, and an environmental impact assessment, necessary to evaluate the impacts of those flows [73].

The materials flows vary a lot by the different authors. For example the amounts of fertilisers and pesticides used depend by the crop type, climate and environmental condition, country.

According to the soil and seed type, land area and location, type and quantity of fertilisers, there will be generated different inventory analysis and environmental impact results.

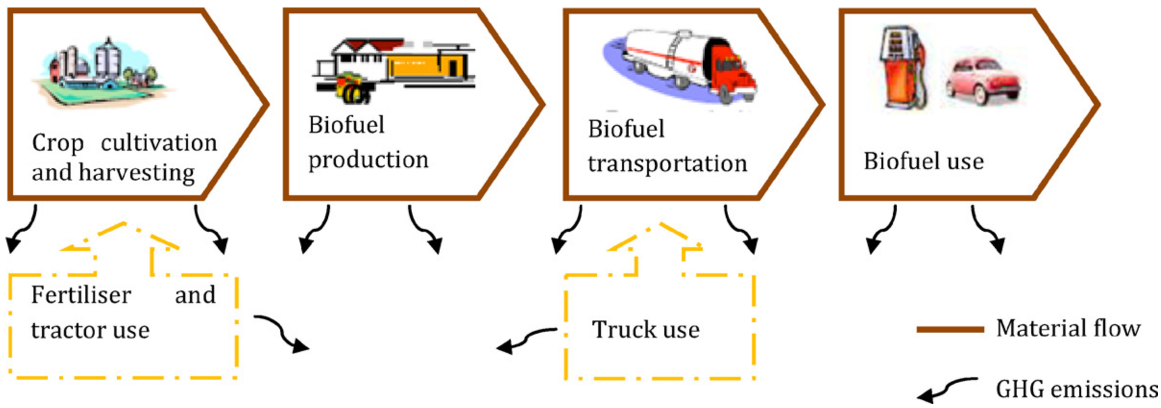


Fig. 5. Schematic biofuel production chain. The reference flow is one unit of biofuel use, i.e. 1 vehicle km.

Considering seed type, land location and type and quantity of fertilisers is possible identify some inventory categories and then the respective environmental impacts. For example, from the seed type and cultivation depend the energy inputs and ratio oil/press cake (inventory categories), but also the air pollution, water depletion, soil fertility, climate change (environmental impacts). The use of fertilisers and pesticides brings to heavy metal deposition on the soil, with consequently water pollution, eutrophication and ecotoxicity problems.

4.1. Life cycle energy analysis

For the life cycle analysis first of all it is necessary to determine the fossil energy ratio, defined as the ratio of final fuel product energy to the amount of fossil energy required to produce and distribute the fuel. Hossain and Davies [66] define the fossil energy ratio equal at 1.20 MJ, which is the total energy required for production of 1 MJ of fossil diesel. This 1.20 MJ fossil energy ratio corresponds to a life-cycle output-to-input energy ratio of 0.83 [127]. Has been measured that approximately 93% of the total primary energy requirement is used for crude oil extraction. The energy ratio for bio fuels depends on the plant oil specie and local climate conditions, type and efficiency of agricultural machineries, mode of transport and conversion processing technologies. Janulis [117] in his study settled that all energy ratios depend on climatic conditions and on the agro and processing technologies used. The life cycle energy balances vary when fuel is produced by the cold pressing and low productivity oil transesterification equipment and when fuel is produced by high productivity hot pressing and transesterification production technology. Application of more efficient oil extraction and transesterification technology increases energy efficiency indices substantially [117]. In the Hossain and Davies [66] study the energy ratios for fossil diesel, rapeseed oil and rapeseed biodiesel are reported as 0.88, 3.2–3.5 and 1.9, respectively.

In Fig. 6 are reported the results obtained from the above mentioned authors, during their life cycle analysis.

It is clear that the use of pure plant oil (here soybean oil) in CI engines presents noticeable advantages respect to soybean biodiesel and fossil diesel related to input energy ratio.

4.2. Life cycle GHG emission analysis

GHGs emission come out along the entire biofuel production chain. All the literature reviews agree in stating that the environmentally most critical biofuel chain's process is crop cultivation. During this stage most of CO_2 and N_2O emissions are generated by land use and transformation.

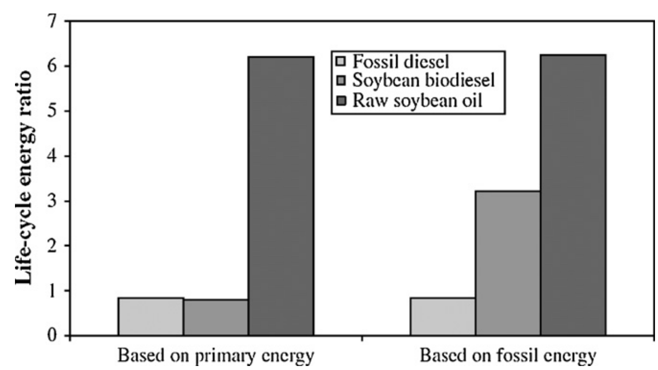


Fig. 6. Life cycle output to input energy ratio of fossil diesel, soybean biodiesel and raw soybean oil [9].

To assess GHGs emission impact is used the Global Warming Potential (GWP) index. It has been created in the Kyoto Protocol to measure the potential of gases or volatile liquids to heat up the atmosphere. Due to the extremely low heat conductivity of the GHGs when released they traps heat in the atmosphere.

Therefore, GWP index is used to translate the level of emissions of various gases into a common measure, to compare the relative radiative forcing of different gases. It is calculated over a specific time interval, generally 100 or 500 years. GWP is expressed as a factor of carbon dioxide then called CO_2 equivalents. In a 100 years time horizon, equivalence factors are [75].

- 1 g CO_2 = 1 g CO_2-eq.
- 1 g CH_4 = 23 g CO_2-eq.
- 1 g N_2O = 296 g CO_2-eq

Along this time horizon GWP resulting from emissions of CO_2, CH_4 and N_2O are reported in Table 3.

The final index is calculated from the total GHGs, released all along the value chain, multiplied by the respective equivalence factors.

It is necessary to point out that, while pure plant oil biofuel does not need chemical processing to modify its viscosity, biodiesel does.

Table 3
Global warming potential (GWP) and atmospheric lifetime [76].

GHG	Atmospheric lifetime (years)	GWP[a]
CO_2	50–200	1
CH_4	12 ± 3	21
N_2O	120	310

[a] 100 year time horizon.

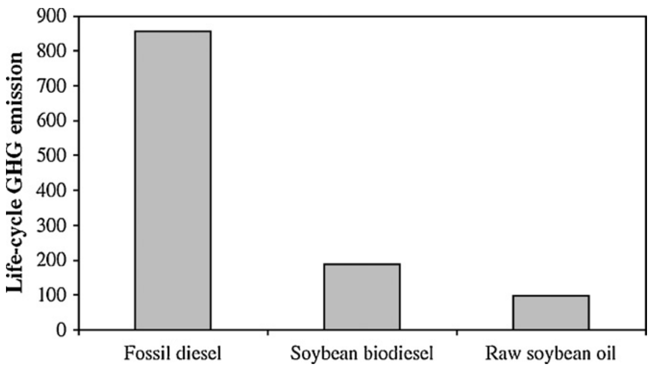


Fig. 7. The graph compares total life cycle GHG emission (g CO_2 equivalent/kW h) of fossil diesel, soybean biodiesel (100%) and raw soybean oil [8].

The absence of the refinery step is translated into lower greenhouse gases emissions for straight vegetable oil.

Analysing the data in Table 4 can be noticed that biodiesel has higher GHG emission respect to fossil diesel and plant oil, during the life cycle. As pointed out in the second paragraph of the paper, biofuels do have more elevated CO_2 and NO_x emissions, but this amount is completely offset by the plantation of new oil bearing plants. Hence the released gases are then totally compensated over the plant oil life cycle.

Moreover N_2O emissions are twice higher for fossil diesel than for plant oil. Nitrous oxide affects 293 times more GWP than CO_2, therefore its reduction carries more importance in the operation of a CI [20,75].

The results obtained by Hossain and Davies [66] are graphically reported in Fig. 7.

The life cycle assessment of biofuel for addressing GHG balance is complex.

By comparing Hossain and Davies [66] study with the results from different life cycle analysis it has to be noticed that the outcomes are not as positive as Hossain and Davies ones. It should be noted that some analysis indicate that some seed-based biofuels may actually increase life-cycle GHG emissions (substantially) respect to petroleum-derived fuels [128].

Due to the large variation in data, inputs and boundary system is not possible to identify which life cycle analysis is more reliable. Certainly it can be stated that an high and ecologically sustainable biomass yields joint to an efficient plant oil conversion process to fuel, are essential parameters to reach higher GHGs savings.

5. Net land requirement for EU biofuels

The new European Union Directive goal is to achieve by 2020 a biofuels' usage target of 10% in transport [80]. To meet this target between 18.5 and 21.1 millions of hectares are needed [90].

Biofuels can be made from anything that is, or ever was, a plant. First-generation biofuels derive from biomass. Applying different technologies the feed stocks (food and feed crops) are converted into biofuels. Since global population growth and an ever increasing demand for land for food supply in the future can be expected there will be competition for land use in order to provide biofuels and maintain enough of and reasonably priced food. Consequently the full development of the biomass option requires a thorough analysis of possible consequences of a major shift in land use.

Therefore a series of studies [43,99,129–131] have been carried out to evaluate the land use requirements for biofuel production.

Table 4
Life cycle GHG emission analysis of fossil diesel, raw soybean oil and soybean biodiesel [9].

GHG/pollutants	Life cycle air emission (g/kW h)										
	Fossil diesel			Plant oil (soybean) and/or biodiesel						Total biodiesel	Total plant oil
	Production, refinery, transport	Diesel tailpipe	Total	Soybean agriculture	Soybean crushing/conversion	Soybean transport	Biodiesel transport	Biodiesel tailpipe	Plant oil tailpipe		
CH_4	0.2718	0.0000	0.2718	0.0379	0.2231	0.0027	0.0011	0.0000	0.0000	0.2648	0.1285
NO_x	0.2795	6.4320	6.7115	0.2696	0.1994	0.1067	0.0289	7.0038	6.4320	7.6076	6.9246
N_2O	0.0091	0.0000	0.0091	0.0017	0.0007	0.0003	0.0003	0.0000	0.0000	0.0031	0.0028
CO	0.0935	1.6080	1.7015	0.1834	0.0310	0.0150	0.0105	0.8646	1.2703	1.1145	1.5033
CO_2 (fossil)	114.2	734.3	848.6			94.54	47.27	41.03	0.0000	182.8	94.54
CO_2 (biomass)	0.0000	0.0000	0.0000			0.0000	0.0000	728.1	769.1	728.1	769.1
Total			857.29							919.89	872.20

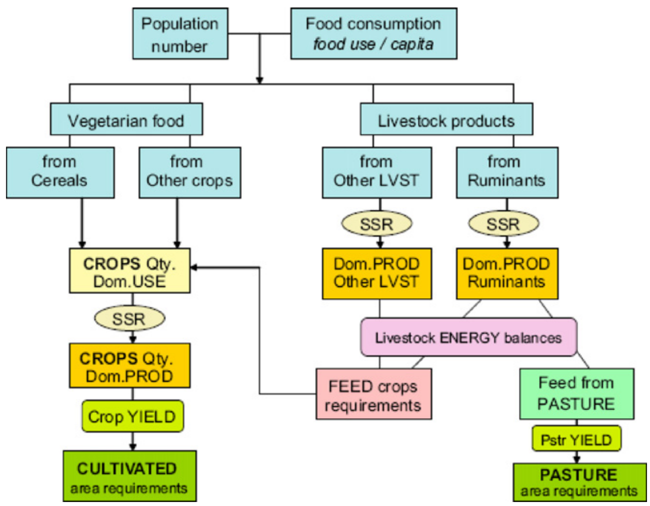


Fig. 8. Flow chart for food and feed area requirements calculation procedures [81].

In a study carried out in China [77] a methodology for estimating water and land footprints[5] was implemented. The water required for harvesting a unit of feedstock crop (CWR) was calculated as the rate between the seasonal water evapotranspiration (m^3/ha) and the crop yield (kg/ha). Then, multiplying this value with the biofuel density and amount of feedstock necessary to yield a kg of biofuel (C), it is obtained the water footprints of a certain biofuel.

The land footprints is calculated as the rate between biofuel density times feedstock conversion ratio (C), and the crop yield.

Results show how the highest water and land footprints is due to soybean feedstock, followed by rapeseed. The important amount of lands and water needed points out that vegetable oils for usage in diesel engines are more suitable for a small scale production for self-supply in agricultural machinery. Other authors [79] highlighted that biofuels need major water footprints than fossil fuels, while fertilisers and other agrochemical products can pollute water bodies, which is an additional issues it must be taken in mind.

Another international study [99,129] estimates the potential lands for biofuel production, classifying three different scenarios:

- a base scenario, in which it is assumed a modest increases in seed oils cultivation, according to the current trends;
- an environment oriented scenario, in which it is assumed a major use of lands, but assuring sustainable farming practices and biodiversity maintenance;
- an energy oriented scenario, in which it is assumed a considerable conversion in land use including pasture lands.

The research work distinguishes between food and feed areas, meaning feed stocks to population or animals use respectively.

To estimates those required areas a function of population number was taken into account, joint to per capita food consumption levels.

The land resources considered in the model were the European ones, with a total agricultural area that includes 164 million hectares of cultivated land and 76 million hectares of permanent grassland.

Fig. 8 provides a schematic overview of the estimating process.

The study led to the conclusion that by 2030 some 22–46 million hectares of cultivated land could be used for bioenergy feedstock production.

[5] Water footprint is a measure of the total volume of water needed to produce goods and services of a nation.

The pasture land contemplated in the energy oriented scenario includes an extra 19 million hectares that could be used as feed stocks for second-generation biofuel production chains. Eastern Europe areas are found to be of noticeable interest, Ukraine's lands can be used to yield crops both for food and feed purpose.

Besides, also agricultural residues of food and feed crops may provide an additional source for biofuel production.

In a study carried on at Stuttgart University (Germany) [90] the opportunity of feeding animals with biofuel side products was investigated. The aim of the work was to find out if those residues were suitable for animal feed, in order to avoid further feed stock cultivation, diminishing the pressures on land area requirements. The utilization of biofuel side products tested with soy seeds in Brazil attested good results, led up to 7.1 million ha of land area savings.

In any case, the production rate of vegetable oils strongly depends on soil fertility, climate and local conditions, thus different regions are focusing their efforts on different types of oil–for example, Jatropha and Pongamia in India and Africa, rapeseed and sunflower in Europe, palm in Malaysia and Indonesia, and coconut oil in Philippines and Sri Lanka [9].

Regarding rapeseed oil, in a study performed for Elsbett Technologie are shown some of its strength points. As it is not grown in tropical regions it does not contribute to deforestation, but its rotation harvesting with cereals every four years helps to maintain long term food yields, lowering the competition with food cereals [82].

Together with edible-oils, also non-edible plant oils has been investigated in the last years. Their usage is particularly interesting as they are generally cheaper than edible-oils, but above all because they, apparently, do not compete with food [83]. The non-edible characteristics could be an advantage only if the land availability is enough for edible and inedible cultivations, and there will be kept a balance between both crop growing. Economic reasons could indeed bring farmers to switch from producing food crops to producing biofuels crops, even if they are non-edible. This situation will then create an unbalanced market condition, for which, if fewer farmers are producing food, the price of food will rise.

Furthermore the studies [43,99,129–131] pointed out the importance of 2nd generation biofuel, on which is necessary to invest more resources in the next years. Lignocellulosic feed stocks plantations are indeed potentially important sources for biofuel production, thus the interest towards these biofuel is rapidly increasing.

6. Conclusions

As a summary from the state-of-the art analysis, amongst biofuels, PPOs can be used to replace diesel oil in CI engines, thanks to their similar physical and chemistry properties. Although their usage in diesel engines is subordinated to some engines modifications, due to their higher viscosity and lower volatility respect to fossil fuels. The most commonly used engine adaptation refers to the injection system and is successfully operated by several car manufacturers, the one presented in the paper was the Elsbett Technologie.

The benefits coming from the use of PPOs as fuel for diesel engines have been exposed and are here summarised:

- they are biodegradable and renewable fuel, thus they are environmentally friendly,
- compared to fossil fuel they have a lower sulphur content,
- they have flash point higher than that of diesel oil, thus are safer for use,

- CO_2 emissions from diesel engines are absorbed by plants growth as feedstock for the following plant oil usage, reducing GHGs emissions,
- they are produced in rural areas and can contribute to the local economy,
- their agricultural residues from crops production can be used to feed animals or as potential source for 2nd generation biofuel,
- they can improve security of energy supply, strengthening the national economy.

Besides this, with the actual knowledge technologies, the current rate of world fuels demand and the large land requirements for feedstock, plant oils are unlikely to substitute the majority of fossil diesel consumption.

Research is needed to increase productivity by species selection, optimisation of the biofuel production chain (building up a conversion system from feedstock to end products for example), engine modifications, on-farm processing technology, methods for maximising oil extraction, feed stock regulation.

The amount of biofuel production should be a trade-off between the need of land for food production and the need of land for industrial production, giving priority not to its market demand but to its production capacity.

As long as the technology to run vehicles will not change, PPOs offer an option to fossil fuel. They are good candidates to substitute a small to medium portion of petroleum, making a significant contribution as renewable fuel. Although a diversification in the energy sources is required to supply the worldwide fuel consumption.

They are an excellent solution in feeding agricultural machinery, since they can be directly produced locally in a short supply chain offering the extra fuel needed to enhance agricultural production. This is particularly important for developing countries and rural areas, because it will help to reduce the fossil fuel imports and balance the payments balance strengthening the local economy.

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